5. RESULTS AND DISCUSSION: THE SEDIMENTS

CHEMICAL OXYGEN DEMAND AND TOTAL VOLATILE SOLIDS

Since measurements of chemical oxygen demand (COD) and total volatile solids (TVS) are often linear functions of one another and each represents a rough gauge of relative organic carbon concentrations, they will be discussed together in this report. In reality, the presence of oxidizable and volatile inorganic compounds may significantly augment the variability of their interlinearity, and neither analysis should be treated as an absolute measure of organic carbon content.

A summary of COD and TVS values from the four Lake Union stations, is given in Table 5-1, together with data from selected sites in the Duwamish River, the Lake Washington Ship Canal, the Sammamish River, and Lake Sammamish. Sampling sites are shown in Figs. D-1 and D-2 in Appendix D.

Two observations may immediately be made on the basis of the data from Lake Union alone: a significantly lower organic content of sediments at Station 518 (the Fremont Bridge) compared with the other three stations and a significant seasonal fluctuation in organic content of inlake sediments. The first inference is supported by visual evidence of the predominance of sand in sediments at Station 518 and of dark, soft muck in sediments at Stations 522, 526 and 532. The magnitude of the (apparently) seasonal fluctuation in sediment organic matter is somewhat surprising, however. For cores taken from Lake Washington, Shapiro et al. (1971) recorded a maximum <u>net</u> increase in organic content (TVS) of about 2 percent/year, as opposed to the 2.3-8.2 percent increases observed over a 7.5-month period in Lake Union. It seems probable, therefore, that the word "net" is deservedly emphasized. The rapid buildup of organic debris occurs under conditions of stratification, when the organic byproducts of spring and summer algal blooms sink into an anoxic hypolimnion. On the basis of sedimentation rates given in Section B-6 and a maximum estimated sediment sampling depth of 1.5 cm, up to 40 percent of the material sampled in September may have been deposited since the previous sampling. Much of this material may well have been subsequently dissipated by chemical and physical processes following the autumn overturn. A thorough analysis of organic fluctuations in core samples would be required for this cycle to be fully quantified.

The present data do clearly indicate, however, that the sediments of Lake Union are richer in organic content than those of most other local bodies of water. The only

Table 5-1. Summary of Chemical Oxygen Demand and Total Volatile Solids in Sediments at Stations sampled in Lake Union and other Local Bodies of Water

a. Lake Union

DATE	STATION	COD (% Dry Wt.)	TVS (% Dry Wt.)
2/7/74	518	4.1	3.6
9/20/74		4.4	5.4
12/18/74		4.1	
2/7/74	522	9.7	14.1
9/20/74		27.4	22.3
12/18/74		8.4	
2/7/74	526	23.1	21.5
9/20/74		29.9	24.1
12/18/74		21.2	
2/7/74	532	22.2	23.7
9/20/74		27.2	26.0
12/18/74		29.5	

b. Duwamish Waterway[1]

DATE	STATION[2]	COD (% Dry Wt.)	TVS (% Dry Wt.)
7/25/72	D1	10.4	23.2
7/25/72	D2	7.7	6.6
7/25/72	D3	4.6	6.0
7/25/72	D4	8.0	7.7
7/25/72	D5	7.6	11.6
7/25/72	D6	6.1	8.3
7/25/72	D8	6.7	11.3
7/25/72	D9	0.3	1.4

c. Lake Washington Ship Canal[3]

DATE	STATION[4]	COD (% Dry Wt.)	TVS (% Dry Wt.)
7/71	1		6.3
7/71	2		11.2
7/71	3		19.0
7/71	4		10.9
7/71	5		19.7
7/71	6		22.7
7/71	7		62.7
9/75	M1	3.9	7.4
9/75	M2	5.5	18.1
9/75	M3	0.4	3.6
9/75	M4	39.6	37.5
9/75	M5	14.9	16.9
9/75	M6	1.6	5.9

d. Sammamish River[5]

DATE	STATION	COD (% Dry Wt.)	TVS (% Dry Wt.)
5/5/71	SR1	16.0	
5/5/71	SR2	1.8	
5/5/71	SR3	0.8	
5/5/71	SR4	0.3	
5/5/71	SR5	0.3	
5/5/71	SR6	0.3	
5/5/71	SR7	0.3	

e. Lake Sammamish[6]

DATE	STATION[7]	COD (% Dry Wt.)	TVS (% Dry Wt.)
9/21/66	S1	29.7	18.5
9/21/66	S2	26.7	30.3
9/21/66	S3	26.9	20.6

(1) Analyses by Stevens, Thompson & Runyan, Inc. for the U. S. Army Corps of Engineers (STR, 1972).

(2) Post-1963 dredging history: D1-12/64; D2 through D5 - none; D6-12/64; D8-12/64, 6/68; D9-12/64, 6/68, 5/71.

(3) Stations 1-7, sampling and analysis by J. M. Kniseley Engineering Corp. for the U. S. Army Corps of Engineers; Stations M1-M6, sampling and analysis by Metro.

(4) Last dredged in 1959.

(5) Metro data.

(6) Ibid.

(7) All three stations located in alluvial fan of Tibbett's Creek (within 100' of mouth) at the southern end of the lake.

other locations from which consistently high COD and TVS values have been obtained are Portage Bay and the Tibbett's Creek delta in Lake Sammamish. There are also some indications of high organic loading in Salmon Bay and Union Bay.

The consistently high organic concentrations in Lake Union probably reflect a higher net increased rate of sedimentation as a by-product of the reduced in-lake circulation. Increased productivity stimulated by algal nutrients from wastewater overflows may be a significant secondary influence. However, the present data are insufficient to confirm this.

There is also an apparent tendency for the deep holes in the northeast and southwest sectors of the lake to trap an uncommonly large fraction of the circulating "bedload." The associated sedimentation rates will be further delineated below.

OILS AND GREASES

A comparative summary of concentrations of oils and greases in the sediments of Lake Union, the Duwamish waterway, and the Lake Washington Ship Canal is given in Table 5-2. These data also reflect the highly contaminated condition of the Lake Union sediments. Concentrations at Station 522 were at least twofold those at any location outside the lake, and those at Station 526 were two-thirds of those at Station 522. High oil and grease concentrations were measured outside of Lake Union only at Salmon Bay, Portage Bay, and the mouth of the Duwamish River. The implications of this distribution are discussed in Section B-9 in conjunction with an analysis of the separation into hydrocarbons and fatty matter. This chromatographic separation of the total oil and grease samples into the polar and nonpolar fractions provides further clues to the origin of significant build-ups.

TOTAL ORGANIC NITROGEN AND TOTAL PHOSPHATE

Sediment samples from the four Lake Union stations were also analyzed for total organic nitrogen and total phosphate concentrations and their respective water-soluble components. Analyses for soluble fractions were run on the filtrate from samples leached overnight in deionized, distilled water (see Appendix A). The results are presented in Table 5-3, together with comparable data from other local water bodies. Unfortunately, ammonium persulfate digestion was used for the total phosphate analysis instead of the more efficient method of perchloric acid digestion used by many other investigators. Thus, the digestion of sediment was very

Table 5-2. Summary of Oil and Grease Concentrations in Sediments of Lake Union and other Local Bodies of Water

a. Lake Union

Date	Station	O & G (% Dry Wt.) Total	Animal/Veg. Origin	Petroleum Origin
9/20/74	518	0.19	0.06	0.13
	522	1.59	0.78	0.81
	526	1.06	0.63	0.43
	532	0.58	0.04	0.54

b. Duwamish Waterway(1)

Date	Station(2)	O & G (% Dry Wt.)
7/25/72	D1	0.65
	D2	0.32
	D3	0.12
	D4	0.33
	D5	0.20
	D6	0.10
	D8	0.14
	D9	0.04

c. Lake Washington Ship Canal(3)

Date	Station(4)	O & G (% Dry Wt.) Total	Animal/Veg. Origin	Petroleum Origin
9/75	M1	0.29	0.21	0.08
	M2	0.72	0.69	0.03
	M3	0.31	0.08	0.23
	M4	0.82	0.69	0.13
	M5	0.36	0.34	0.02
	M6	0.16	0.16	0.00

(1) Analyses by Stevens, Thompson and Runyan, Inc. for the U. S. Army Corps of Engineers (STR, 1972).

(2) See Table 5-1 for post-1963 dredging history.

(3) Metro data.

(4) Last dredged in 1959.

Table 5-3. Summary of Organic Nitrogen and Total Phosphorus Concentrations in Sediments of Lake Union and other Local Bodies of Water

a. Lake Union

Date	Station	Total Org. N (mg/kg dry Wt.)	Sol. Org. N (mg/kg dry Wt.)	Total P (mg/kg dry Wt.)	Sol. Total P (mg/kg dry Wt.)
2/7/74	518	2100	608	40	40
9/20/74		3110	1070	1410	83
2/7/74	522	7470	1950	1040	192
9/20/74		7970	3460	629	290
2/7/74	526	13900	4760	1170	494
9/20/74		12200	5120	2700	574
2/7/74	532	17100	6220	1480	620
9/20/74		11100	4300	1530	130

b. Duwamish Waterway(1)

Date	Station(2)	Total Org. N (mg/kg dry Wt.)	Total P (mg/kg dry Wt.)
7/25/72	D1	1450	290
7/25/72	D2	1820	190
7/25/72	D3	320	340
7/25/72	D4	1090	250
7/25/72	D5	1460	550
7/25/72	D6	1210	250
7/25/72	D8	1480	330
7/25/72	D9	210	240

c. Lake Washington Ship Canal(3)

Date	Station	Total Org. N (mg/kg dry Wt.)
9/75	M1	1220
9/75	M2	3460
9/75	M3	170
9/75	M4	10100
9/75	M5	4170
9/75	M6	792

d. Lake Washington(4)

Date	Station	Total Org. N (mg/kg dry Wt.)
8/27/71	W1	2942
8/27/71	W2	3883
8/27/71	W3	4181
8/27/71	W3a	3556
8/27/71	W4	3369
8/27/71	W5	2018

e. Lake Sammamish(4)

Date	Station	Total Org. N (mg/kg dry Wt.)
7/15/71	S 1	2142
7/15/71	S 3	3796
7/15/71	S 5	1144
7/18/71	S 7	4296
7/18/71	S 9	4122
7/18/71	S11	4357
7/18/71	S13	5678
7/23/71	S15	4240
7/23/71	S17	4789
7/23/71	S19	4356
7/23/71	S20a	5479
7/23/71	S22	10508
7/21/71	S23a	9207
7/23/71	S24	4185
7/23/71	S25a	5007

(1) Analyses by Stevens, Thompson & Runyan, Inc. for the U. S. Army Corps of Engineers (STR, 1972).
(2) See Table 5-1 for post-1963 dredging history.
(3) Metro data.
(4) Horton (1972)

likely incomplete in the present instance and resulted in only a partial recovery of the total phosphate (O'Connor and Syers, 1975). The data are included in the table as they are representative of values obtained by a standard procedure and indicative of relative magnitudes in Lake Union as compared with the Duwamish waterway. On the other hand, the ammonium persulfate method is believed to be adequate for digestion of dissolved metaphosphates and polyphosphates; therefore, recovery of the soluble total phosphate fraction will be considered complete for the present analysis.

The total organic nitrogen concentrations in sediments were found to be higher at Stations 526 and 532 than at any other location considered. (Table 5-3). Portage Bay (M4) and a single station in Lake Sammamish were nearly as high in this regard. The fraction of total nitrogen in the sediment organic matter (based on TVS) was fairly consistent, amounting to 2.2 ± 1.6 percent for 18 stations in Lake Union, the Lake Washington Ship Canal, and the Duwamish Waterway. As a consequence, it is not surprising that the distribution of total organic nitrogen tends to reaffirm the conclusions drawn in the discussion of the regional distribution of sediment organic matter.

HEAVY METALS

Sediment cores were taken from each of the four principal sampling stations on September 20 and December 18, 1974, cut into 2-cm segments (see Appendix A for details), dried, and analyzed by atomic absorption spectrometry for cadmium, chromium, nickel, copper, zinc and lead. Since the surface fraction of the sediments is often disturbed or lost entirely in the coring process, we overlaid the metals profiles for the two cores at each station to superimpose prominent features, rather than present them strictly by sediment depth. Mean concentrations were then calculated for physically coincident core segments, and the results were plotted by depth, on the assumption that the resulting topmost values were representative of the sediment-water interface. At each station the same core profile overlap was used for all six metals. The consequent mean profiles are given in Fig. 5-1.

As will be discussed later, the sedimentation rates at the various stations (determined by ^{210}Pb dating of core segments) were found to be extremely variable. Consequently, the present commentary is restricted to consideration of sediment surface concentrations and metal profile configurations for individual stations. For example, it is apparent that much of the copper, zinc, and lead in the sediments came from the same source(s), as evidenced by the extensive within-station similarities of these three profiles. Also, there are scattered indications of profile similarities for

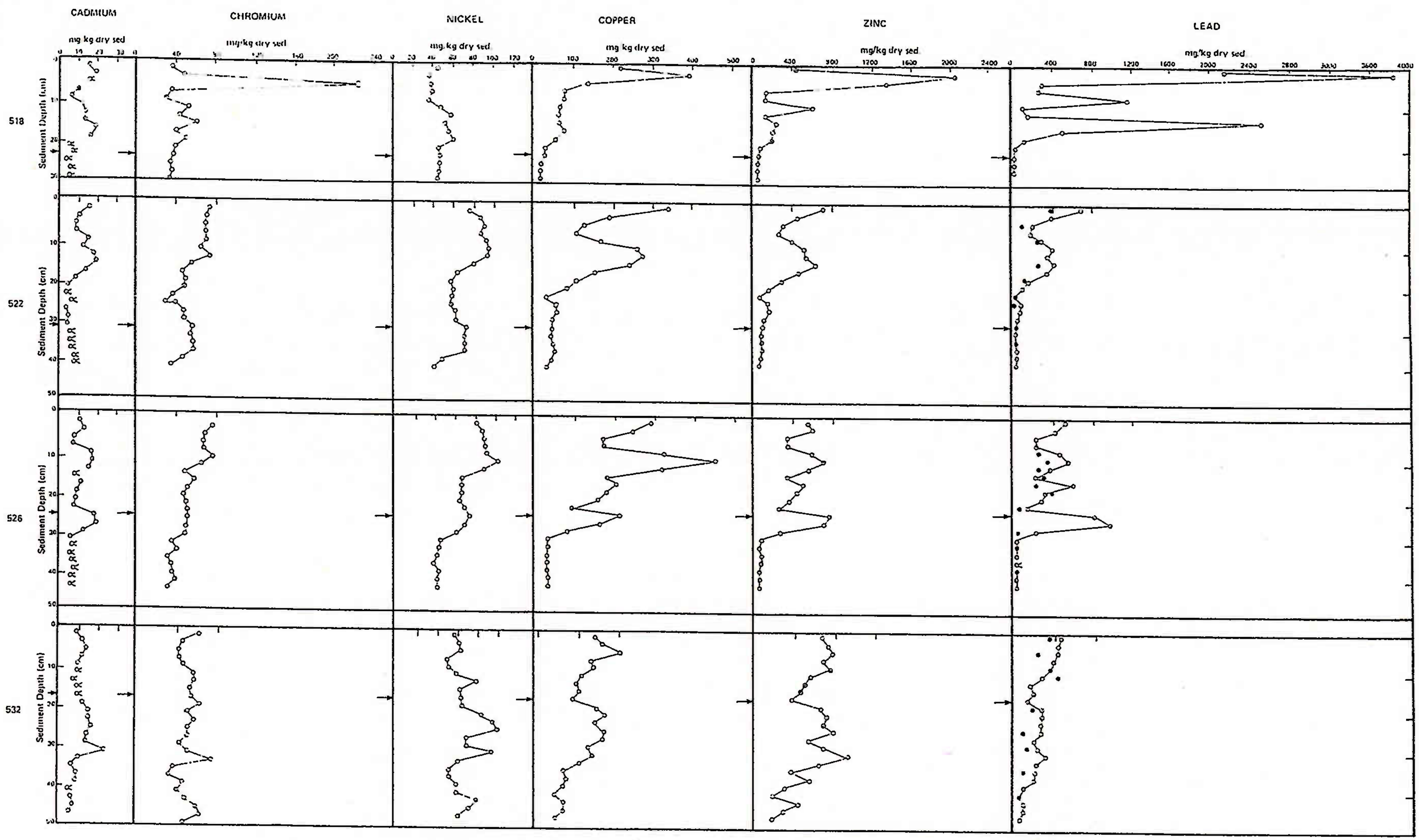


Fig. 5-1. Distribution profiles for heavy metals in Lake Union sediments, 1974.
Symbols — ⊙: Metro analyses (AAS), ⊛ UW Lab of Radiation Ecology analyses (AAS), →: maximum penetration depth of shallowest core (values above this level are means for two cores), ⊙< : maximum value (detection limit).

certain other combinations, such as Cd, Ni, Cu, Zn, and Pb for the depth interval 23-31 cm at Station 526, and for all six metals between 13 and 21 cm at Station 522. The top 20 cm of the core taken at Station 518, which consisted of deposits laid down since 1954, when the ship canal was last dredged, showed scattered evidence of severe contamination with Cr, Cu, Zn, and Pb.

Substantial increases in the sediment concentrations of Cu, Zn, and Pb over the years were evident at all stations, but were similar for the two in-lake stations, 522 and 526. Increases over pre-industrial (i.e., pre-1890) baseline concentrations averaged 13 times for Cu, 10 times for Zn, and 22 times for Pb, whereas fourfold increases have been reported by Barnes and Schell (1973) for Zn and Cu near the Evergreen Pt. Bridge in Lake Washington. Compared with contemporary mean surface sediment concentrations determined for 18 sites in northern Lake Washington (Spyridakis and Barnes, 1976), the mean concentrations of Cu, Zn, and Pb for Lake Union are higher by factors of 5.6, 3.3, and 3.0, respectively.

The changes were more extreme but quite erratic for Station 518 and about one-half as great for Station 532. Both of these sites showed high sedimentation rates; and the more recent deposits, laid down since the construction of the Montlake Channel in 1916, must have been appreciably diluted with sediments of low-metal content. Station 518 has apparent local sources of contamination.

Similarly, the in-lake concentrations (Stations 522 and 526) of Cr and Ni had approximately doubled, whereas those in the channel (Stations 518 and 532) had not significantly changed. The concentrations of Cd remained comparatively constant at all four locations.

The sediment surface concentrations of Pb, Zn and Ni are compared with contemporary values for Duwamish River sediments in Table 5-4. The Pb concentrations in Lake Union were appreciably higher (a mean of 24x) than those in the Duwamish River. Moreover, the mean Zn and Ni concentrations of the four Lake Union stations were higher by a mean factor of 2.6x.

This difference cannot have come from dredging, since the river stations D1 through D6 had not been dredged since December 1964, so that there was a buildup of undisturbed sediments for 10 years (D8 was dredged during June 1968). Part of the difference may be due to higher sedimentation rates in the Duwamish and an appreciable dilution of the metal contaminants from high inputs of low-metals

Table 5-4. Summary of Heavy Metals Concentrations in Sediments of Lake Union and the Duwamish Waterway

a. Lake Union

Date	Station	Lead (mg/kg dry sed.)	Zinc (mg/kg dry sed.)	Nickel (mg/kg dry sed.)
12/18/74	518	1120	436	44
9/20/74,(1) 12/18/74	522	324	692	74
12/18/74	526	163	258	88
12/18/74	532	450	323	55

b. Duwamish Waterway(2)

Date	Station(3)	Lead (mg/kg dry sed.)	Zinc (mg/kg dry sed.)	Nickel (mg/kg dry sed.)
7/25/72	D1	0	319	35
7/25/72	D3	13	81	19
7/25/72	D4	59	201	30
7/25/72	D5	10	162	29
7/25/72	D6	7	116	30
7/25/72	D8	32	122	27

(1) Mean values for two cores.

(2) Analyses by Stevens, Thompson and Runyan, Inc. for the U. S. Army Corps of Engineers (STR, 1972).

(3) See Table 5-1 for post-1963 dredging history.

sediments originating further upstream. However, since much of the sediments input occurs in the industrialized Duwamish Valley, it is not safe to assume that the metals content at the point of origin was necessarily low. Indeed, with so many unknowns involved in the comparison, the reasons for the discrepancies in concentration between these two bodies of water cannot presently be determined. The relative potential for a detrimental influence on the biota is a little clearer and more importantly emphasized.

6. RESULTS AND DISCUSSION: THE BIOTA

PHYTOPLANKTON

Methods

The phytoplankton biomass in Lake Union was measured in terms of cell densities (total cell volume per unit volume of water) and chlorophyll a concentrations. Chlorophyll a concentrations were measured at four depths at Stations 522 and 532 and at the surface and bottom at Stations 518 and 526; phytoplankton cell densities were determined for the surface only (1 m depth). The data are summarized in Figs. 6-1 and 6-2.

Analysis of transparencies obtained by secchi disk (Fig. 6-3) suggests that phytoplankton productivity in Lake Union was predominantly confined to the surface waters. If it is assumed that the relationship among sampling depths, secchi disk readings, and the depth of light extinction for Lake Union is the same as described by Emery (1972) for Lake Sammamish, rough estimates indicate that the euphotic zone in Lake Union in 1974 was confined to depths of less than 10 m except in October. The secchi disk measurements of the two lakes are similar, with minima near 2 m and maxima near 5 m. The mean value in 1974 for Lake Union was 3.1 m. The high values read at all stations in late October, indicating relatively high water clarity, were due to a combination of conditions, including maximum bottom salinities and minimum winds, that resulted in a high degree of stratification at a time when light and nutrient levels were no longer favorable for algal blooms.

Although high chlorophyll a concentrations were present at 10 m and the bottom (Fig. 6-1) and microscopic examination revealed algal cells in samples from these levels, these phytoplankters were considered to be below the compensation depth. It was further noted that the same algal species occurred at all depths. Therefore, it was concluded that the high chlorophyll a concentrations near the bottom consisted of sinking cells rather than growth in situ. Pieterse (1974) came to a similar conclusion regarding a high density of *Oscillatoria agardhii* detected far below the euphotic zone in Lake Washington. Because there appeared to be no further growth in these sinking algal cells at 10 m and the bottom, they were neither identified nor counted.

The chlorophyll a concentrations were fairly similar at 5 m and the surface of Lake Union in 1974. At no time did high chlorophyll concentrations appear at depth without similar indications at the surface.

The possibility of phytoplankton layering at specific depths has been mentioned by Whitmore et al. (1974) for three other

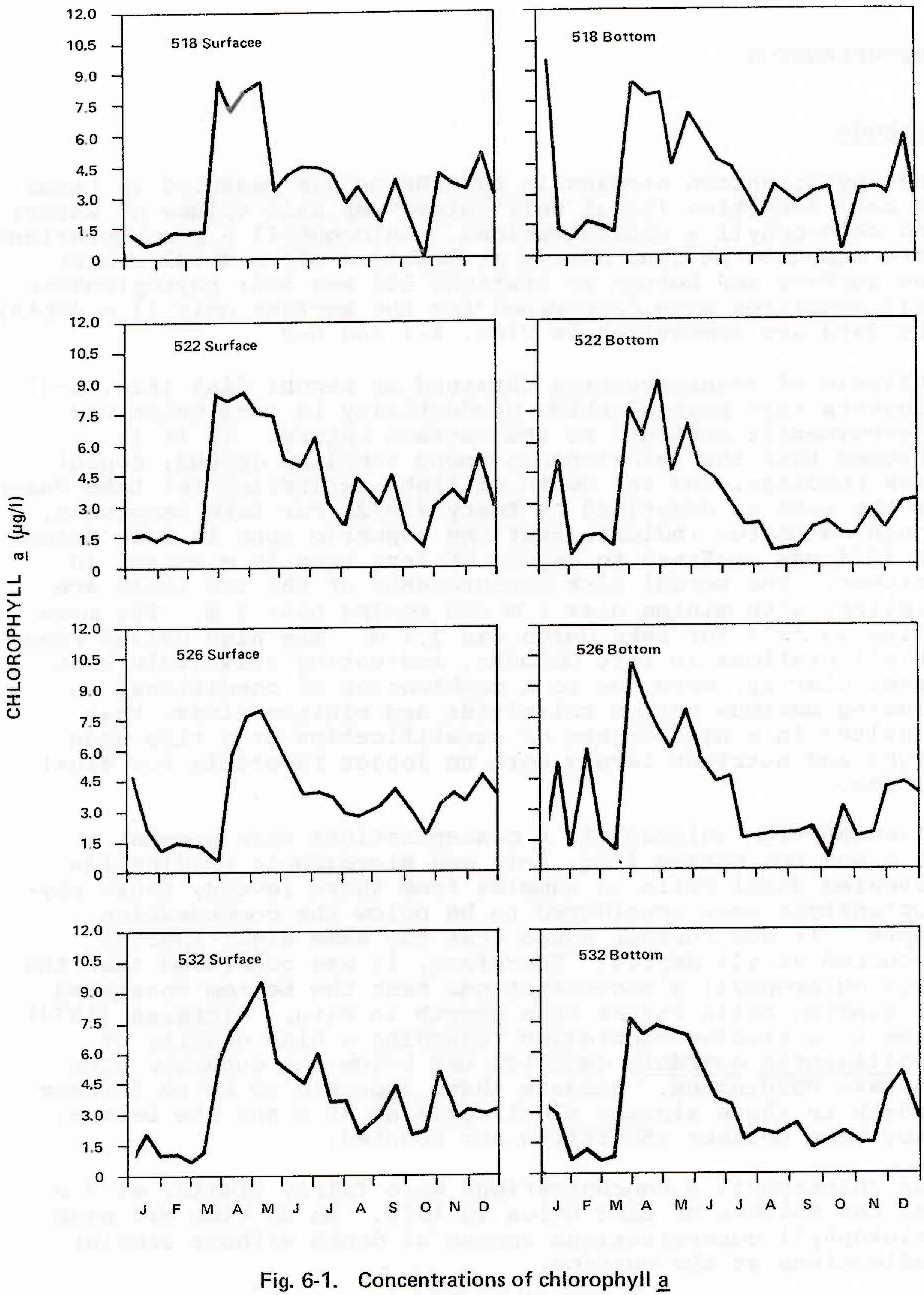


Fig. 6-1. Concentrations of chlorophyll a at the surface and bottom of Lake Union, 1974.

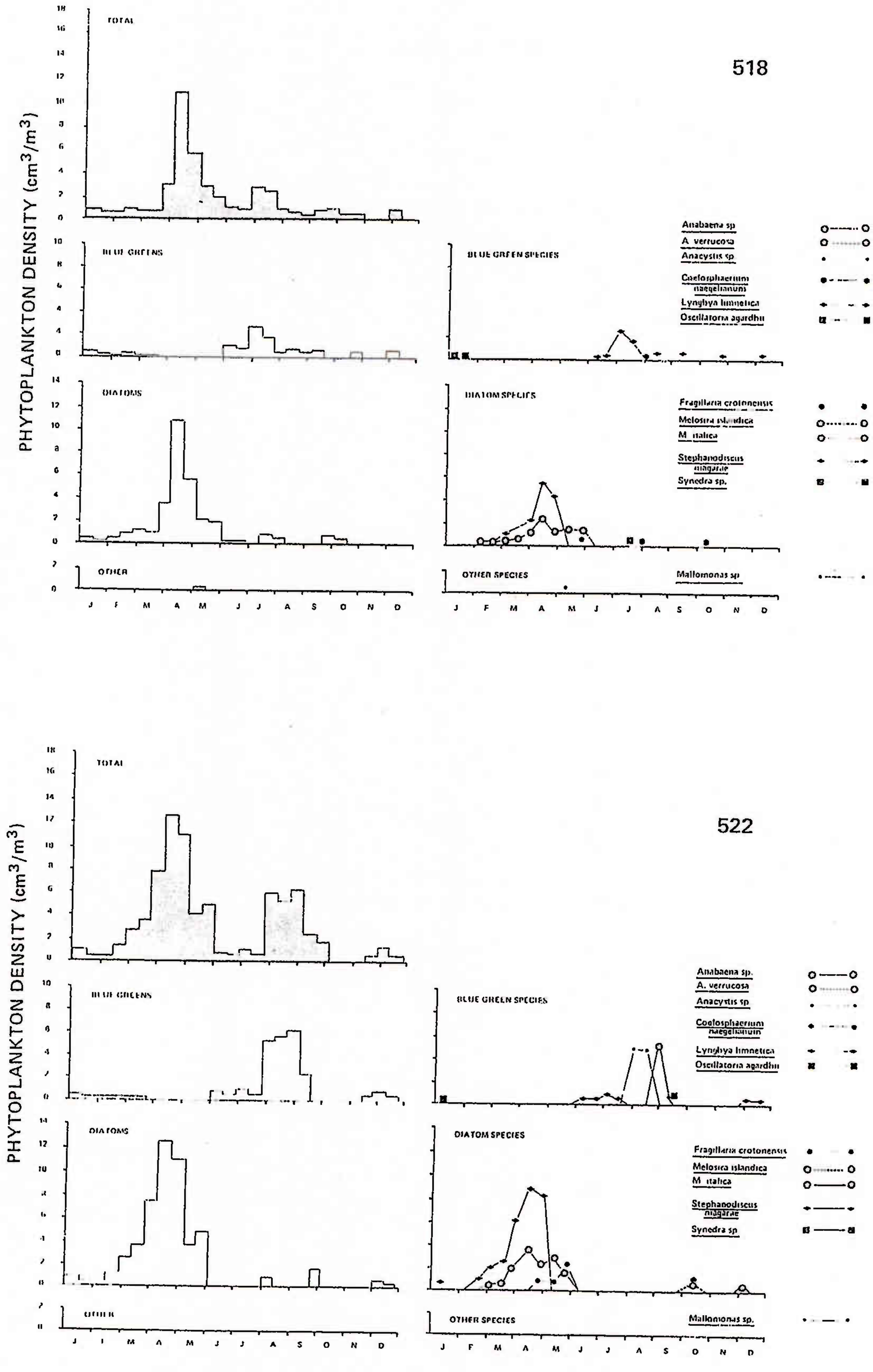
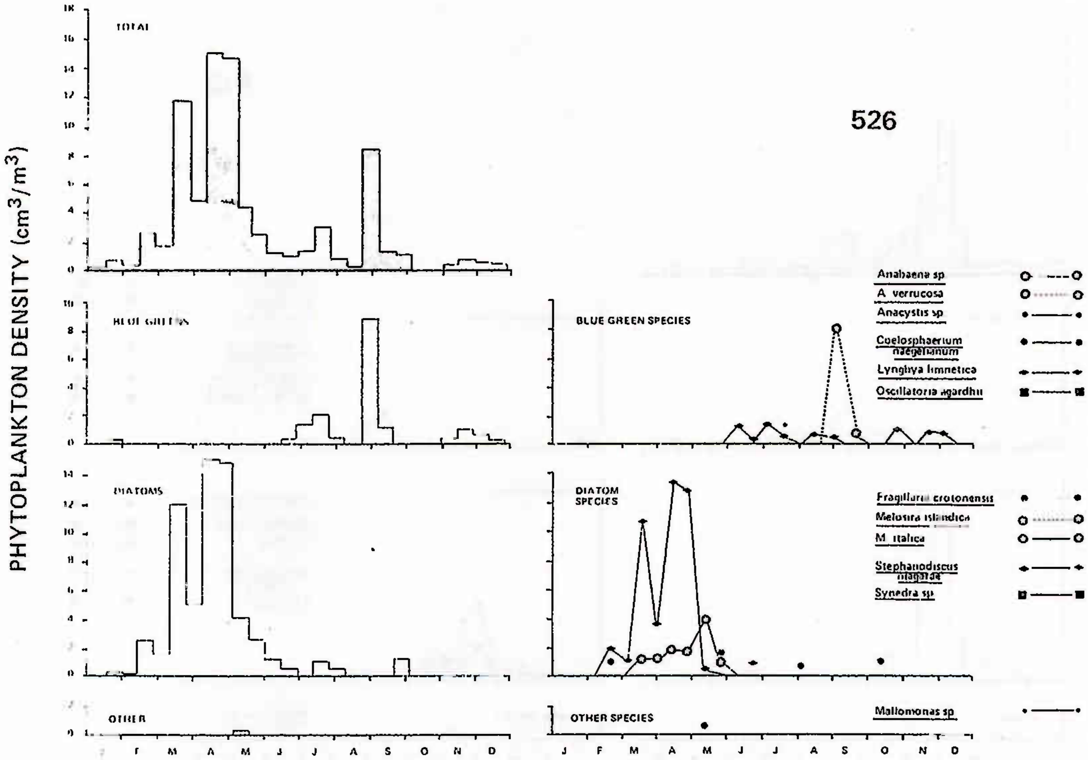


Fig. 6-2. Phytoplankton cell densities at the surface (1 m) of Lake Union, 1974.



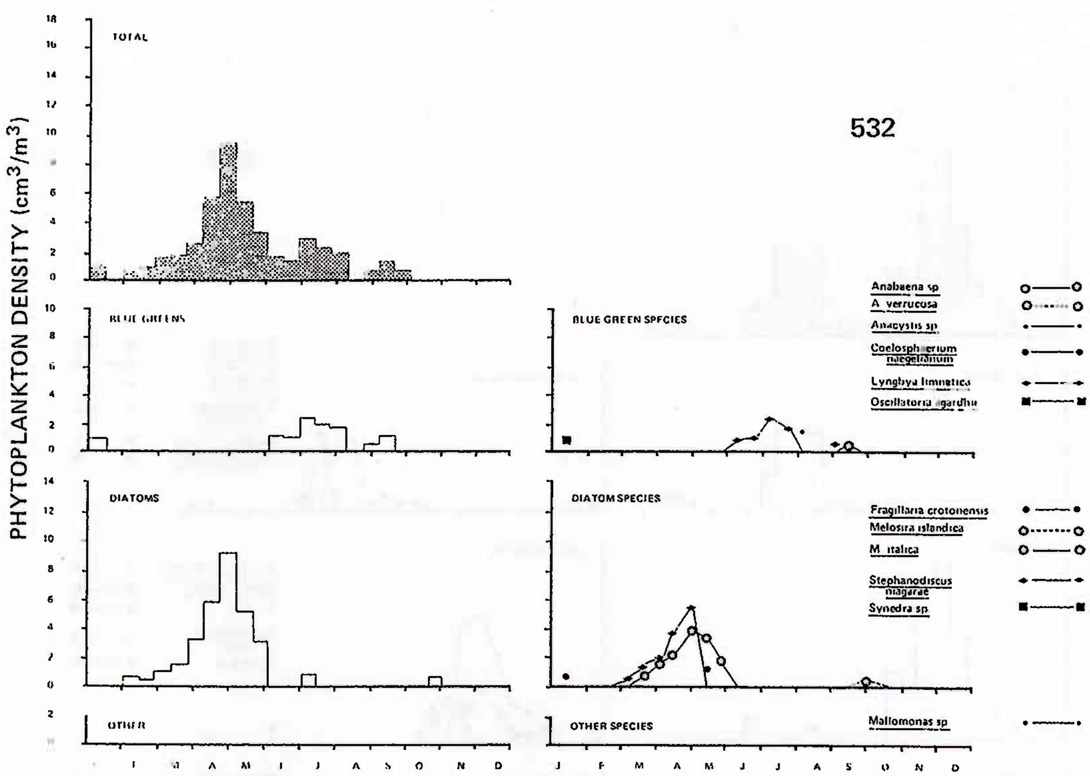


Fig. 6-2. (Continued)

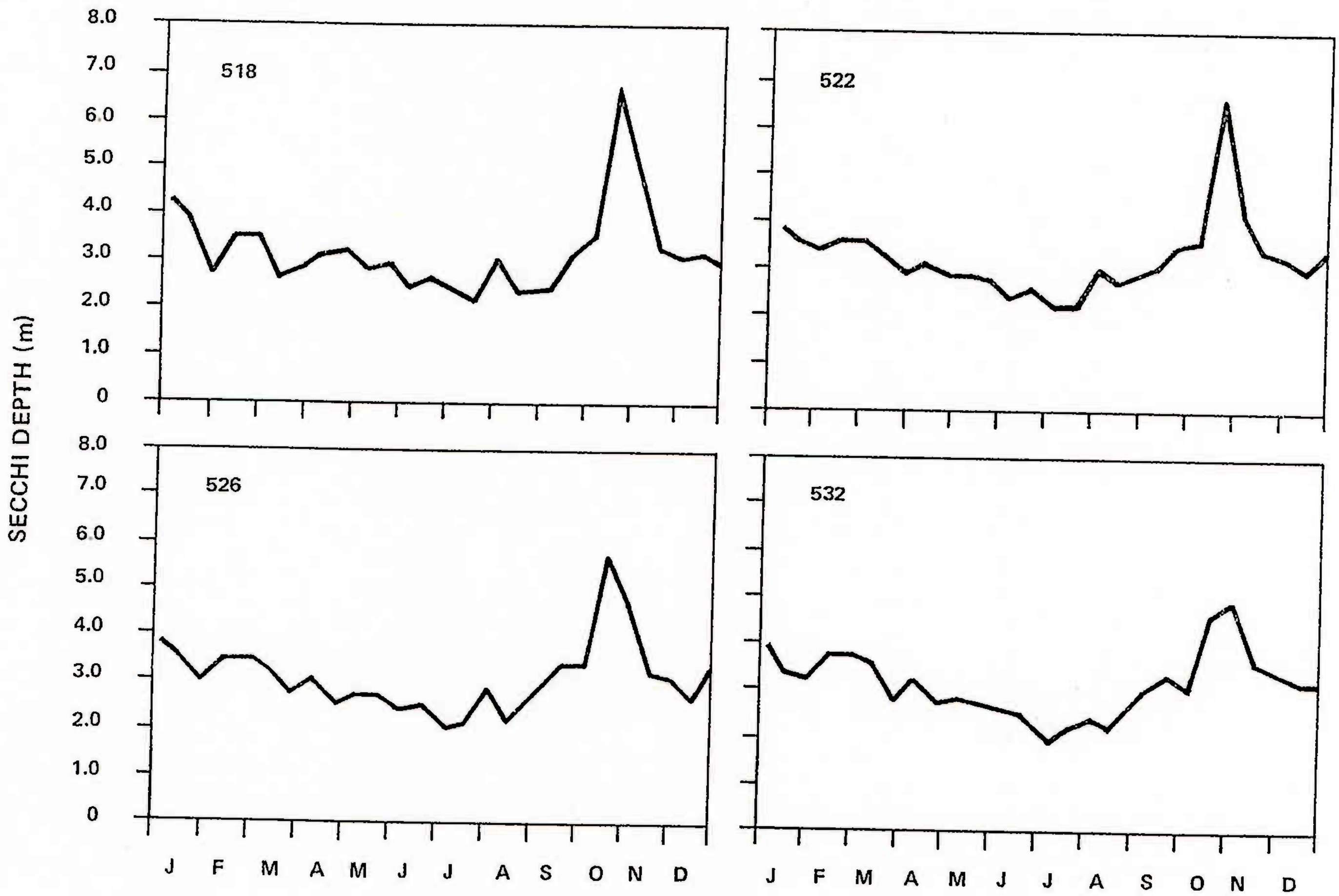


Fig. 6-3. Secchi disc readings in Lake Union, 1974.

King County lakes (Pipe, Wilderness, and Cottage). The phenomenon was not investigated in Lake Union. It might be of considerable interest to search for layering with a transmissometer and subsequently sample and microscopically examine dense populations detected. Pieterse (1974) used this technique in Hall and Haller Lakes, and found dense, microstratified populations in layers 1 to 2 m thick.

Generic Composition and Distribution

The phytoplankton genera identified at the four Lake Union stations are listed in Table 6-1. Rare genera (less than 4 organisms/ml) are not included. In general, the same blue-green, diatom, and cryptophyte genera were found at all stations. However, major station-to-station differences appeared in the occurrence of the green algae and the non-diatom chrysophytes.

Under certain conditions, diversity indices have been used as indicators of trophic state, but Rawson (1956) has argued against doing so, contending that the number of genera observed at a given location is as much a function of the intensity of sampling and observation as it is of actual occurrence. Consequently, an analysis of in-depth diversity of the present data was not attempted. Superficial observations suggested that Station 522 had the greatest generic diversity and Stations 518 and 526 had the least, but the statistical significance of these differences was not calculated.

It was initially intended for this section to include a detailed comparison of the genera and abundance estimates of phytoplankton in Lake Union with those available for Lake Washington (Edmondson, unpublished) and Lake Sammamish (Emery, 1972). However, important differences in methods negated the utility of such a comparison. The existence of these other data is noted here specifically for the benefit of future investigations.

Species Succession and Bloom Dynamics

The phytoplankton cell densities (Fig. 6-2) and chlorophyll *a* concentrations (Fig. 6-1) at the surface are indicative of the annual fluctuations in biomass in the euphotic zone. During 1974, primary producers in Lake Union appeared to consist predominantly of diatoms in the spring, blue-green algae in the summer, and a mixture of the two throughout the fall and winter. The data on phytoplankton cell density have been subdivided here so that different major algal groups will stand out. The major groups are further subdivided to the species level. Organisms with densities of less than .5 cm^3/m^3 were not recorded.

These data designate a relatively low phytoplankton population consisting mostly of blue-green and diatom species from January until March.

Table 6-1. Phytoplankton Genera at Four Stations in Lake Union, 1974

X = Genera Present (more than 4 organisms/ml sample)

Genera	STATIONS 518	522	526	532
Cyanophyta (blue-green algae)				
Chroococcus		X		X
Anacystis	X	X	X	X
Coelosphaerium	X	X		X
Oscillatoria	X	X	X	X
Lyngbya	X	X	X	X
Anabaena	X	X	X	X
Aphanizomenon	X	X	X	X
Chlorophyta (green algae)				
Chlamydomonas	X	X	X	X
Eudorina		X		
Gloeocystis	X		X	X
Tetraspora		X		
Sphaerocystis	X	X		X
Ankistrodesmus	X	X	X	X
Kirchneriella		X		
Oocystis		X	X	X
Quadrigula	X	X	X	X
Dictyosphaerium	X		X	
Coelastrum				X
Crucigenia			X	
Scenedesmus	X	X		X
Pediastrum			X	
Elakatothrix			X	
Arthrodesmus		X	X	X
Staurastrum		X		
Closterium	X	X	X	X
Euglenophyta (euglenophytes)				
Trachelomonas	X		X	
Cryptophyta (cryptophytes)				
Cryptochrysis	X	X	X	X
Cryptomonas	X	X	X	X
Rhodomonas (?)	X	X	X	X
Chrysophyta (yellow-green algae)				
Ochromonas		X		X
Uroglena		X		
Dinobryon		X	X	
Mallomonas	X	X	X	X
Synura	X	X		X
(diatoms)				
Melosira	X	X	X	X
Cyclotella	X	X	X	X
Stephanodiscus	X	X	X	X
Rhizosolenia	X	X		X
Asterionella	X	X	X	X
Diatoma	X	X	X	X
Fragilaria	X	X	X	X
Synedra	X	X	X	X
Tabellaria	X	X		X
Navicula	X	X	X	X
Cymbella	X	X	X	X
Nitzschia	X	X	X	X

In March, the spring bloom of phytoplankton began. In terms of volume, Stephanodiscus niagarae was the dominant species, and Melosira italica was the subdominant species. The Melosira populations entered the rapid growth phase and reached peak biomass concentrations a little later than the Stephanodiscus populations. As is to be expected, the increase in phytoplankton biomass was accompanied by decreases in surface phosphate (Fig. 4-10) and nitrate + nitrite (Fig. 4-12). The blooms were probably stimulated largely by increased water temperatures and solar radiation, both of which increased substantially in March.

It is of interest to note that Lake Washington also had blooms of Melosira italica and Stephanodiscus niagarae (as well as S. astraea) at this time (W. T. Edmondson, personal communication). It is quite possible that the blooms in Lake Union were seeded by the advection of cells from the larger lake.

By May 9, when the lake had begun to stratify thermally, the blooms had started to decline. After May 23, the diatom peaks were no longer evident. At that time the concentrations of assimilable nitrogen and phosphorus were below Sawyer's (1974) bloom-limiting nutrient criteria (see discussion of eutrophication). Concentrations of ortho PO_4-P in the euphotic zone were within the range .003-.006 mg/l, and inorganic N concentrations were .141-.191 mg/l. Further, the onset of stratification would have cut off the nutrient supply from the hypolimnion. It therefore seems probable that the dieoff of phytoplankton was brought on by nutrient depletion or limitation, although insufficient data are available to enable an analysis of the role of the grazing of zooplankton.

After the spring diatom bloom came a period of low phytoplankton biomass. The total cell volume was made up mostly of the blue-green species, primarily Lyngbya limnetica. Warm waters may have favored the growth of this species (Pieterse, 1974). NO_3 + NO_2 - N concentrations continued to decrease and fell to very low levels (.010 mg/l) during June and July. The limited availability of nitrogen may in fact have been responsible for the inability of the Lyngbya population to grow any further, as Lyngbya is not a known nitrogen fixer.

Very patchy distributions of blue-green algae developed at Stations 522 and 526 near the end of summer. These organisms were not evident at Stations 518 and 532. The population densities remained comparatively low at Stations 522 and 526, but the species and bloom durations differed between them. Comparatively slow water circulation at this time may have been the major factor responsible for the uneven bloom distribution. It is of interest to note that blooms of Anabaena spp. occurred at Stations 522 and 526 on September 5, when orthophosphate levels appeared to be too low to support primary production. Although concentrations of inorganic nitrogen were also low, it may have been supplied through nitrogen fixation, a process of which Anabaena has been shown to be capable (Whitton, 1975).

Table 6-2. A Summary of Water Quality Problems Observed in Selected Lakes of the Lake Washington and Green River Drainage Basins, 1973-74 (After Uchida et al., 1976)

Categories	Union (1974	Angle (1973)	Ballinger (1973)	(1974)	Beaver #2 (1973)	Cottage (1973)	(1974)	Crystal (1973)	Desire (1973)	Meridian (1973)	(1974)	Morton (1973)	Pine (1973)	Pipe (1973)	Sawyer (1973)	Serene (1974)	Silver (1973)	Star (1974)	Stickney (1973)	Wilderness (1974)	TOTAL
Physicochemical																					
1-Dissolved O_2 conc. ≤ 1.0 mg/l (bottom)	x	x	x	x	x	x	x	x	x	x	x		x	x	x		x	x	x	x	18
2->50% of samples have D.O. ≤ 4.0 mg/l (bottom)							x	x			x							x	x	x	6
3-Spring, surface inorganic $\overline{N} \geq 0.30$ mg/l	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		18
4-Spring, surface total hydrol. $PO_4 \geq 0.02$ mg/l	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	20
5-Bottom temp. ≥ 20.0 °C												x				x					2
Biological																					
6-Mean summer chl. a >10 µg/l																					
7-Max. phyto. cell density >3 cm^3/m^3						x	x		x				x								4
8-Bloom freq. >25% of samples	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	19
9-Large, colonial blooms of blue-green algae, summer dominant	x		x	x		x	x		x		x		x			x			x	x	11
10-Macrophytes present in >25% of shoreline			x	x		x			x				x					x		x	7
11-Spring, summer median total coliform count >240 org./100 ml,						x	x	x						x		x		x			6
or >20% of samples have 1000+ org./100 ml.	x			x		x	x	x											x		6
12-Spring, summer geometric mean of fecal coliform count >200 org./100 ml, or >10% of samples have 400+ org./100 ml.				x			x														2
TOTAL	6	2	6	8	4	9	10	7	7	4	6	4	7	5	4	6	4	7	7	6	

Notes on Categories:

1,2) High dissolved oxygen demand of bottom waters detrimental to biota and indicative of eutrophication.
5) High bottom temp. detrimental to cold-water fish.
6-9) Phytoplankton conditions associated with eutrophication.
10) Dense macrophyte growth interferes with recreational use of the lake.
11-12) Lake sanitation below state or federal standards in spring and summer months.

September 19 was the last sampling date on which evidence was found of the dominance of blue-green algae. In early October, the surface waters of the lake began to cool significantly, and the phenomenon may have strongly affected the competitive balance for those species present. For the remainder of the year the phytoplankton standing crop was very low, with blue-green algae and diatoms randomly dominant.

Of the other local bodies of water, the following lakes have a frequency of algal blooms similar to that of Lake Union (Uchida et al., 1976): Ballinger, Meridian, Sawyer, Serene, Star, and Stickney.

Lake Classification

A comparison of problems with water quality in Lake Union with those of other regional lakes has been provided in Table 6-2. This summary is based on a relative water quality rating scheme developed by Uchida et al. (1976) for data from the 1973/1974 Metro small lakes program. We have included it here to put the Lake Union data into a perspective familiar to a wider range of readers.

In general, the problems with water quality in Lake Union are high spring nutrients and coliforms, high summer algal concentrations, and low bottom oxygen values. These problems are seen to be common to many of the other degraded lakes in the region. These lakes were originally selected for study from a larger list on the basis of known or suspected problems of water quality. It may be of further interest to note that Lakes Ballinger and Pine, rated as having only slightly poorer water quality than Lake Union, are presently under consideration by local and regional interests for rehabilitation.

ZOOPLANKTON

The water column at Station 522 was sampled for zooplankton with a vertical 1-m ring net on September 18, 1975. The organisms collected are listed in Table 6-3. Deterioration of pertinent structures due to delays between the times of collection and examination made identification of some species difficult.

Table 6-3. Zooplankton Observed at Lake Union Station 522, September, 1975

Cladocerans:	Diaphanosoma leuchtenbergianum(?) Daphnia sp. Leptodora kindtii
Calanoid Copepods:	Osphranticum labronectum(?) Diaptomus sp. Epischura nevadensis
Mysid Shrimp:	Acanthomysis awatchensis
Rotifers:	Various species, including Keratella cochlearis

The planktonic fauna was dominated by species of Daphnia and Diaptomus. The mysid, Acanthomysis, is primarily a brackish-water form (Chace et al., 1959) found in isolated bodies of freshwater and in freshwater basins narrowly connected with the sea. In Lake Union, it is probably associated with the saline hypolimnion. However, the functional integration of a water column as sampled by a vertical ring net defies depth estimates for specific organisms.

A single sampling of zooplankton would not provide any data on seasonal abundance, dominance, or the response of these organisms to phytoplankton blooms. This information is important for a complete understanding of the food chain relationships and the related impacts of man-made contamination. Unfortunately, insufficient time was available for work on zooplankton in the present study and it must therefore be recognized as one of the most significant deficiencies in our data record.

BENTHIC MACROFAUNA

The distribution of macroscopic animal life on and in the sediments of Lake Union appears to be extremely dependent on depth and/or location. None was found in grab samples taken during 1974 at Stations 518, 522, 526 and 532. Whether this sterile condition reflected the influence of low oxygen concentrations, high levels of sediment contaminants, and/or other factors, one can only speculate.

On the other hand, an abundance of segmented worms (oligochaetes), mollusks (pelecypods and snails), and insect larvae (chironomids) was found in grab samples taken near the southeastern shore by Shepard (1973, 1974) during the previous year. A summary of Shepard's data, together with faunal densities calculated for this report, appears in Table 6-4. In addition to those groups mentioned above, the cladocerans and copepods were present in significant numbers, even though these organisms are predominantly planktonic and do not strictly belong in this assemblage.

Another benthic organism that occurs in both Lake Union and Lake Washington in significant numbers is the crayfish. During the period August - October, 1975, 33 sets made with crayfish pots near the southeastern shore of Lake Union yielded 436 adult crayfish (C. R. Hitz, personal communication). Extensive data on the sex and size of these organisms were also recorded.

FISHES

Shepard (1973, 1974) documented catches of fish taken with various types of nets in southeastern Lake Union, near the Seattle City Light power plant. Fishing was conducted with floating and sinking gill nets set during daylight and nighttime hours and on one occasion, with a Fyke net (bottom-operating fish trap) set overnight. The data are given in Table 6-5.

Table 6-4. Summary of Benthic Macrofauna Observed in Sediment Samples from Southeastern Lake Union* (data from Shepard, 1973)

Data	Depth (m)	Grab	Oligochaeta	Pelecypods	Chironomid larvae	Cladocera	Copepods	Snails	Chironomid pupae	Nematodes	Hydra	Unidentified
9/14/73	5.0	A	387	43	14		19				PRESENT	
		B	15	2								
	6.5	A	39	1	2	1						
		B	27	4		1						
	8.0	A	3			1						
		B	6									
	8.0	A	5			7						
		B	1									
Mean no. organisms/m^2:			2600	269	86	54	102					
9/26/73	5.0	A	3		2	4	2	2	1		PRESENT	
		B	5				1	2		1		
	6.5	A	167	11	5	1		1	1			
		B	170	14	9	2	5					
	8.0	A	3			2	5					1
		B			3	3						
	8.0	A	5					4				
		B	2		1	4						
Mean no. organisms/m^2:			1911	134	108	86	70	48	11	5		5
10/15/73	5.0	A	24	1	1	2	2				PRESENT	
		B	5	1	4	7						
	6.5	A	1	1	1							
		B	14		1	6						
	8.0	A				2						
		B				1						
	8.0	A	2									
		B	1									
Mean no. organisms/m^2			258	16	37	97	11					

* All grabs taken near Fairview Avenue, in the vicinity of the Seattle City Light Power Plant intakes and outfalls. Sampler: 6- by 6-inch Shipek grab.

Table 6-5. Summary of Fish Captured in Southeastern Lake Union (Data from Shepard, 1973, 1974)

COMMON NAME & SPECIES	SAMPLING DATES (1973) 9/12	9/14	9/26	10/5	10/5-6	10/9	10/17	10/17-18	11/8-9	11/13-14	11/19-20	Totals
Yellow Perch (*Perca flavescens*)	11/B		4/B	5/B		28/B	15/B	9/B*				63/B, 9/B*
Peamouth (*Mylocheilus caurinus*)	7/B	12/B	4/B			1/B	1/B	1/B*				25/B, 1/B*
Northern Squawfish (*Ptychocheilus oregonensis*)	3/B	4/B				2/B		2/S*, 5/B*	3/S*	2/S*		9/B, 5/B*, 7/S*
Largemouth Bass (*Micropterus salmoides*)	1/B				3/F*							1/B, 3/F*
Black Crappie (*Pomoxis nigromaculatus*)					1/F*							1/F*
Brown Bullhead (*Ictalurus nebulosus*)								1/S*		1/S*		2/S*
Coho Salmon (*Oncorhynchus kisutch*)								4/S*	2/S*	2/S*	2/S*	10/S*
Chinook Salmon (*Oncorhynchus tshawytscha*)											1/S*	1/S*

* Net set and left overnight
S Surface gillnet (100'x6')
B Bottom gillnet (100'x6')
F Fyke net (bottom-operating fish trap)

Yellow perch, peamouth, and northern squawfish were most abundant. They were captured predominantly near bottom under both light and dark conditions, but some squawfish were also found near the surface at night.

The sunfish, consisting of largemouth bass and black crappie, were apparently much more wary. With one exception, catches were taken near the bottom at night in a Fyke net, which traps fish in an enclosure rather than snares them.

The salmon caught were of two species, coho and chinook, and were all taken by floating gillnets set overnight. The single chinook salmon was a juvenile; one half of the coho salmon were adults, ranging from 2.3 to 6.1 kg in weight and 59 to 87 cm in length. Although Ajwani (1958) has noted that coho, chinook, chum and sockeye salmon, steelhead, and searun cutthroat trout all spawn in the Lake Washington drainage basin and must therefore pass through Lake Union, their capture in the southern part of the lake seems surprising. During the same time of the year in 1974, surface and bottom water temperatures were near the upper limit preferred by migrating coho (15.6 °C) as specified by Bell (1973). Also, the waters deeper than approximately 12 m had oxygen concentrations lower than the accepted minimum level of 5 ppm. Bell has stated that fish will generally avoid areas of low oxygen levels and will ultimately seek cooler waters if held in waters with temperatures near their upper tolerance level. It therefore seems likely that the captured salmon were not in a delayed phase of their migration; they may have been following the shoreline on their passage through the lake and were probably avoiding the deeper waters. Regardless of the interpretation, an unknown percentage of migrating coho (and presumably other salmonids also) apparently linger in Lake Union during their transit through the main traffic channel at the northern end. These fish are exposed to any toxic contaminants that might be present and are therefore subject to any associated deleterious effects.

A brief literature review indicates, as might be expected, that all of the fish as found by Shepard (1973, 1974) in Lake Union also occur in Lake Washington. Costa (1973) ranked yellow perch, peamouth, and squawfish as first, second, and third in terms of catch per unit effort for Lake Washington; this ranking corresponds directly to Shepard's ranking for Lake Union. Nishimoto's (1973) data also agree fairly well with these rankings; he found that the four most abundant species in catches by gillnet along the Lake Washington shoreline were (in order): peamouth, yellow perch, northern squawfish, and largescale sucker.

The apparent frequency of occurrence may vary considerably from one area to the next, however. Brown (1968) found that brown bullheads accounted for 77 percent of his total overall catch using modified hoop nets near Kenmore, in Union Bay, and in "the ship canal adjacent to the University of Washington"

(Imamura [1975] calculated a population of 21,289 brown bullheads for Union Bay in 1971). Black crappie made up an additional 9.7 percent of Brown's catch. Perch, sunfish, sculpin, tench, carp, peamouth, squawfish, and sockeye and coho smolts were also captured. The predominant species in collections along the Lake Washington shore by Stein (1970) taken by electrofishing was the prickly sculpin. Sculpins and yellow perch were the only fish sighted by SCUBA divers during a September, 1973 inspection of a building platform on the northeastern shore of Lake Union near Station 532 (City of Seattle, 1973).

7. SUMMARY

THE WATER

Salinity

Stratification began in April and intensified during June and July. Salinities were relatively constant until early August, ranging between .00 and .12‰. At that time, the first salt water intrusion raised the level to .90‰ in the deepest parts of Lake Union. This value increased to 1.6‰ with the second intrusion in October. The lake had been partially mixed by September winds. Overturn occurred in mid-November.

Temperature

The temperature rose from a mixed-lake minimum of 6 °C in January to a mid-September, near-bottom maximum of 19 °C The surface maximum, 22.5 °C, occurred in early August.

Dissolved Oxygen

Dissolved oxygen levels at the surface decreased from 12.5 mg/l in April to 7.5 mg/l in October. The April-to-September (annual minimum) deep-lake change was from 12.5 to 0.0 mg/l. The bottom waters were partially reoxygenated by wind mixing in September and October.

Turbidity

The turbidity values varied between .5 and approximately 2.0 JTU for most of the year. During periods of high runoff, January through March, some spikes in excess of 6.0 JTU were observed near the bottom. Minima were observed at all depths coincident with the arrival of the first salt water intrusion in early August.

Suspended Solids

With the initial establishment of stratification in June, levels of suspended solids fell to nearly zero. Otherwise, values fluctuated between 0 and approximately 5 mg/l for most of the year. Some high near-bottom measurements of 30 to 36 mg/l were recorded in January, and scattered peaks of up to 30 mg/l were observed at various depths in August and early September.

Phosphate

The average surface orthophosphate concentration for the year was .02 mg PO_4-P/l, and the surface maximum was .096 mg PO_4-P/l. In January, February, June, July, and October substantial surface-to-bottom peaks were observed at all stations. Between July and November massive buildups (as high as .31 mg PO_4-P/l) of phosphate were observed in the deepest parts of the lake. These increases coincided with increases of iron under low oxygen conditions. The high phosphate concentrations were no longer evident following the overturn and reoxygenation of the hypolimnion in November.

Iron

The general trends near the bottom corresponded directly to those given for phosphate. Concentrations at the surface averaged .1 mg Fe/l over the year, with transient peaks at the in-lake stations in April and early December.

Nitrate + Nitrite

Nitrate + nitrite levels reached a maximum of approximately .4 mg NO_3 + NO_2 -N/l during February and March, gradually declined to .01 mg NO_3 + NO_2 -N/l in July at the surface and in late September near the bottom, and began to increase again following the fall overturn in November.

Ammonia

The pattern at depth for ammonia was approximately the inverse of that for nitrate + nitrite. Low spring and postoverturn levels were separated by a substantial peak (up to .57 mg NH_3-N/l) coincident with low oxygen concentrations. Peak concentrations (up to .13 mg NH_3-N/l) were measured at the surface at all stations in late October.

Heavy Metals (Other than Fe)

Station-to-station differences were generally insignificant. Persistent concentrations of all of the metals studied (Cd, Cr, Ni, Cu, Zn, and Pb) were probably within recommended environmental limits published under the aegis of EPA. The statement is qualified because the EPA limits for Ni and Pb are below the detection limits of the instrumentation used by Metro.

Coliforms

Both total and fecal coliforms were most abundant during the months of high runoff (Jan-Mar, Nov and Dec). Overall, counts of total coliforms were lower in the NE arm than in the other parts of the lake. This observation is consistent with the six-year (1970-1975) means and is thought to be due to the effects of the prevailing seaward circulation on the distribution of wastewater from overflows. Coliform levels at all four stations exceeded the limits specified by the Washington State Department of Ecology for lake class waters. Throughout the water column, fecal coliform levels were low and nondescript. Total coliform profiles (measured only in a deep hole near the southwestern shore) showed substantial increases near the bottom exactly coincident with the arrival of the first saltwater intrusion. The source of these high concentrations was not immediately apparent. Data on coliform abundance in the Lake Washington Ship Canal over the past 12 years indicate a reduction by an order of magnitude due predominantly to sewage-diversion programs.

THE SEDIMENTS

Chemical Oxygen Demand/Total Volatile Solids

The sediments under the Fremont Bridge (predominantly sand) were significantly lower in organic content than those of the other three stations. At all in-lake stations, there was a significant seasonal fluctuation of the organic content; an increase in TVS of 2.3 to 8.2 percent dry wt was apparent during summer stratification. The sediments of Lake Union were found to be richer in organic matter than those of the Duwamish Waterway, the Sammamish River, and most of the Lake Washington Ship Canal. The only other local sites yielding consistently high COD and TVS values were Portage Bay and the Tibbett's Creek delta in Lake Sammamish. Salmon Bay and Union Bay also gave indications of high organic loading.

Oils and Greases

The oil and grease concentrations at the Lake Union station near Metro's Galer Street outfall were at least twice as high as those determined for various sites in the Duwamish Waterway and the Lake Union Ship Canal. A midlake sample had two-thirds as high a concentration as the Galer Street sample. High oil and grease values were also listed for Salmon Bay, Portage Bay, and the mouth of the Duwamish.

Total Organic Nitrogen/Total Phosphate

The TON concentrations in sediments were found to be higher in the deep parts of Lake Union than at any location considered in the Lake Washington Ship Canal, the Duwamish Waterway, Lake Washington, and Lake Sammamish. Portage Bay and a station in Lake Sammamish also had quite high concentrations. The fraction of total nitrogen bound in sediment organic matter (based on TVS) was fairly consistent, at 2.2 ± 1.6 percent, for 18 stations in Lake Union, the Lake Washington Ship Canal, and the Duwamish Waterway. The total P digestion methodology was considered inadequate, and the data obtained were listed only for their spatial and temporal relativity.

Heavy Metals

Extensive within-station similarities among the core profiles of Cu, Zn, and Pb indicate that these metals were contributed to the lake by the same source(s). The near-surface sediments under the Fremont Bridge gave evidence in spots of severe contamination with Cr, Cu, Zn, and Pb. Compared with preindustrial (i.e., pre-1890) baseline values, the in-lake sediment concentrations of Cu, Zn, and Pb had increased 13, 10, and 22 times, respectively. The concentrations of Cr and Ni approximately doubled during this time, whereas those of Cd remained essentially unchanged. The Zn, Ni, and Pb concentrations were appreciably higher than in the Duwamish River (these were the only three metals thus compared).

THE BIOTA

Phytoplankton

Primary productivity was thought to be confined mainly to the surface waters. High chlorophyll a concentrations at the surface were invariably accompanied by similar concentrations near the bottom that were deemed indicative of sinking cells rather than in-situ growth. A list of algal genera was compiled and included 7 blue-greens and 18 green species, 1 euglenophyte, 3 crytophytes, 5 yellow-green species, and 12 diatoms. The primary production in 1974 was dominated by diatoms in the spring, blue-green algae in the summer, and a mixture of the two throughout the fall and winter. Lake Union appears to be about average in terms of the number of observed problems with water quality, compared with 16 other lakes in the Lake Washington and Green River drainage basins. The other lakes were originally selected for study from a larger list on the basis of known or suspected problems with water quality.

Zooplankton

Zooplankton sampled at one of the in-lake, deep stations were comprised of cladocerans, calanoid copepods, mysid shrimp, and rotifers.

Benthic Macrofauna

Grab samples taken below 11 m at four stations were devoid of macrofauna. The causative factors for the absence of organisms may include low oxygen content, high salinities, and/or sediment toxicants. Supplementary data from a study done near the southeastern shore demonstrated a large diversity of fauna in shallower water, including oligochaetes, pelecypods, chironomids, cladocerans, copepods, snails, nematodes, and hydra. The worm communities were as dense as 2600 organisms/m^2.

Fishes

Data on net catches from another study indicate the presence of yellow perch, peamouth, northern squawfish, largemouth bass, black crappie, brown bullhead, and coho and chinook salmon in the lake. The literature indicates that these fishes occur also in Union Bay and Lake Washington. A discussion of the physicochemical environment suggests that Lake Union waters are generally hostile for salmonids.

EXPANDED DISCUSSION OF SELECTED TOPICS (Appendix B)

The Saltwater Intrusion

The maximum annual bottom salinity is now only 7 to 10 percent as high as for the period 1925-1953. The hypolimnetic O_2 depletion is also less severe. The threat of net annual salt increases in Lake Washington has been reduced by an estimated 67-94 percent since 1952. Although the stratification of Lake Union is initially established by temperature changes, there is evidence that overturn may be delayed under some circumstances by the stabilizing influence of the saltwater intrusion.

The results of laboratory studies done elsewhere suggest that the saltwater intrusion in Lake Union should have little direct effect on phosphate release from the sediments, but this effect might be expected to increase at higher salinities.

The direct contribution of PO_4 by the intruding seawater is estimated as negligible. A plot of salinity vs zinc concentrations for bottom samples indicates that the saltwater intrusion instigates a release of zinc by the lake sediments. Barring a major malfunction of the lock siphon and/or saltwater barrier, the resultant dissolved Zn concentrations should not exceed .025 ppm. Outside studies have indicated that copper, nickel, and lead may be similarly affected, but instrument limitations prevented a check of the hypothesis in the present study.

The Nitrogen and Phosphorus Budgets

Stream loading is estimated to have contributed more than .05 mg $NO_3 + NO_2$ -N/l (or 13% of the observed spring $NO_3 + NO_2$ maximum) to Lake Union. Similarly annual contributions from dustfall (including fallout on Lake Washington) are calculated to be of the order of .02 mg $NO_3 + NO_2$ -N/l and .055 mg PO_4-P/l for a hypothetical mixed-lake system.

Data from a sewer overflow computer model, together with figures derived from Metro studies of water quality of urban drainage and overflow, provided estimates of the annual wastewater nitrogen and phosphorus loading to Lake Union. The forms of N and P that are usable by phytoplankton are added to the lake in approximately equal concentrations. Stormwater contributes almost as much usable N as combined wastewater does, but only about 9 percent as much usable phosphorus. Most of the wastewater $NO_3 + NO_2$ enters the lake through storm drains. A coherent relationship was found between the soluble total organic nitrogen and the soluble total phosphate in the lake sediments. Organic matter from natural sources and wastewater overflows was postulated to be the prevalent source of both. Of the total organic nitrogen measured, 35.6 ± 6.0 percent was found to be soluble.

Heavy Metals Budget

Estimates of the annual heavy metals loading from wastewater to Lake Union were made in the same manner as those of the nutrients. Lead was found to be discharged in higher concentrations than the other metals (Cu, Zn, Cr and Cd), with a nearly equal contribution by combined and storm wastewater. The loading of zinc, chromium, and cadmium was higher from combined wastewater than from storm water, whereas storm water supplied a large fraction of the copper.

Depth Distribution of Sediment Metals

Estimates of sedimentation rates made for three cores by ^{210}Po-^{210}Pb dating showed a different pattern in each part of the lake. In the center of the lake, sediments between 10 and 20 cm deep were laid down at the rate of 0.16 ± .02 cm/yr; between 30 and 34 cm have been deposited since 1890. In the northeast arm (part of the ship canal channel), the rates were faster and more regular; since 1923, 42 cm have accumulated, at an average rate of 0.80 ± .08 cm/yr. The sedimentation pattern near Metro's Galer Street outfall was not clear; the only definite statement that can be made is that over 36 cm has been deposited there since 1890.

Seasonal Coliform Trends

Geometric mean values of estimated counts of total coliforms for 5 years for selected stations on the Lake Washington Ship Canal show a general increase as a function of distance between Lake Washington and Puget Sound, regardless of season.

However, the increase was significantly lower for the summer/dry season than for the wetter portion of the year. The observed mean counts of total coliforms for stations east of the University bridge were virtually the same for both seasons.

Distribution of Nonparticulate Contaminants

On the basis of the observed trends in coliform abundance, a hypothesis was presented to explain the distribution of nonparticulate contaminants in the lake. This supposition is simply that any quasi-conservative, dissolved, or suspended contaminant characteristically introduced in appreciable quantities by wastewater overflows and/or direct surface runoff will statistically show a linear increase with distance for water moving from Lake Washington to Puget Sound. The southern part of Lake Union is seen to present a partial exception to this rule, owing to a significant decrease in flow rate.

Distribution of Particulate Contaminants

A hypothesis was offered to explain the observed distributions of oils and greases (and other particulate contaminants) in the sediments. Such distributions depend on the location of particle entry or formation in relation to the general water circulation. Thus the sediments were most rich in such contaminants in those locations where the flow rate is lowest (or where the Ship Canal widens), as in Lake Union, Portage Bay, and Salmon Bay.

The sites of particle formation or introduction seem to be fairly evenly distributed. The data indicate, for example, that animal or vegetable-based oils and greases were contributed predominantly by algal blooms, whereas most of the petroleum-based oils and greases were of wastewater origin.

Trophic Classification of the Lake

Lake Union was classified as mesoeutrophic, on the basis of a variety of indices.

Prey-Predator Relationships

A compilation of data from outside sources was offered as a summary of food chain relationships among the zooplankton, benthic macrofauna, and fishes. For the fishes listed, the ten most important food organisms, according to numbers ingested, are (in descending order and weighted by percentage of total diet): dipteran larvae and pupae, mysid shrimp, gastropods, chironomids, sculpins, cladocerans, copepods, juvenile sockeye, crayfish and trichopteran larvae. On the basis of taxonomic or ecological groupings, the prey organisms may be ranked in importance as follows: (1) insect larvae and pupae, (2) planktonic crustaceans, (3) small fish, (4) mollusks, and (5) benthic crustaceans.

8. RECOMMENDATIONS FOR FURTHER WORK

In terms of physical dynamics and the related potential for further contamination, Lake Union is an extremely complex system. Indeed, it may be unique in its triple role as a major inland waterway (in essence, a large embayment of a substantial river), an "estuary" with a "controlled" salt wedge, and as an extensive catch basin for wastewater overflows. The present data and discussion help to describe the intricacies of this system, but several substantial gaps in information need to be closed before any realistic consideration of rehabilitation can be made. Recommendations for further work are listed here in order of decreasing urgency, as regarded by the present authors:

a) Circulation studies. - The calculations presented in this report demonstrate the capacity of a hypothetical, totally mixed Lake Union system to accommodate the dissolved and suspended contaminants introduced by sewer overflows. However, very little is known about the actual characteristics of mixing near shore. Tomlinson et al. (1976) estimated that levels of Cu, Pb, Zn, and DDT from an outfall in northeastern Lake Union remained in excess of 1973 EPA water quality criteria for at least 6 h. In the southern portions of the lake, circulation is more sluggish and wastewater plumes may disperse comparatively slowly, so that the biota of the near-shore areas are subjected to high concentrations of pollutants for extended periods of time. Our knowledge of the toxic effects of combined wastewater on planktonic and benthic organisms is quite limited. It is vital that detailed studies of surface-to-bottom circulation be done under a variety of conditions of runoff and stratification for accurate calculations of plume dispersion to be made. Without this knowledge, the impact of wastewater overflows and localized runoff cannot be realistically assessed.

b) Nutrient budgets. - Lake Union has been shown to be a highly productive, mesoeutrophic lake. Unfortunately, the calculations given here for various components of the macronutrient budgets are based on measurements over a brief period of time and are therefore approximate source-sink estimates. More extensive field measurements are required for a practical understanding of the eutrophication process.

The phosphorus and nitrogen budgets in particular need to be worked out in detail. There are numerous questions to be answered: Is the overall mean phosphate concentration of Lake Union really higher than that of Lake Washington? If so, what are the nature and magnitude of the contributing sources? How much of the dissolved phosphate in the hypolimnion is available for algal uptake before and after mixing and reoxygenation? Does significant phosphate uptake occur in the density interface by phytoplankton from the overlying mixed layer?

What is the average depth of the photosynthesis-respiration compensation point? What is its position in the water column relative to that of the density interface? Would the sediments continue to supply appreciable levels of nitrogen and phosphorus to the surface waters if outside sources were cut off? If so, for how long? What is the actual effect of the saltwater intrusion on the availability of nutrients for algal growth?

The first-order estimates given here of the stormwater nutrient input to the lake can be refined by the application of existing urban storm drainage models to the Lake Union drainage basin. In addition, the water quality of the overflows and discharge plumes needs to be measured directly for representative outfalls around the lake. Historical changes in particulate nutrient concentrations can be quantified and the influence of the saltwater intrusion further defined by analysis of nutrient profiles in sediment cores.

c) Zooplankton dynamics. - Very little is known at this time about the composition and magnitude of, and predation pressures on, the zooplankton populations of Lake Union. Without this knowledge, it is difficult to say whether the algal blooms generally decline from lack of nutrients or from grazing pressure. If the former influence is predominant, then hypolimnetic processes may prove to be the key to the control of bloom magnitude and duration. On the other hand, if grazing pressure is more important, the reduction of pollutant toxicities is even more imperative than previously suggested. Further, quantitative information is needed of predation on zooplankton and its effects on the floral-faunal balance.

d) Distributions of heavy metals, macronutrients, chemical oxygen demand, and oils and greases in surface sediments. - The present data are quite limited and should be augmented by grid sampling of selected areas. Areal contour plots could then be drawn, which in turn could be related to the observed presence or absence of benthic macro-organisms. This program might prove to be an excellent means of identifying important point-sources of contaminants. In particular, the shoreline and outfall areas should be further investigated, together with the possible existence of illegal, uncharted wastewater outfalls.

Such sampling could even provide data to clarify further the influence of hypolimnetic oxygen depletion and the saltwater intrusion on the N and P distributions. To this end, sampling of near-bottom S‰ and D.O., covering the same station grids during midsummer stratification, would provide a comparative map of the lateral extent of the hypolimnion and saline bottom waters.

e) Bioassays. - The absence of benthic macrobiota in the deeper portions of Lake Union may be due to the presence of a variety of influences. These include relatively high salinities, low dissolved oxygen concentrations, and appreciable levels of toxic substances such as heavy metals and petroleum-based oils and greases. Bioassays of lake sediments and water, and organisms from the near-shore areas might permit the separation and assessment of the effects of these parameters.

APPENDIX A: METHODS

SAMPLING

Water

Water samples were collected with a 3-l, hand-operated Van Dorn bottle, placed in ice chests, and kept cold until removal at the laboratory for analysis. Two hours was the maximum elapsed time between sampling and the initial laboratory handling procedures.

Sediments

Sediment surface and core samples were taken with a Van Veen grab and Phleger corer, respectively. Both of these devices were permitted to free-fall through the bottom 5 m of the water column.

Biota

The pelagic biota were obtained with a 3-l, hand-operated Van Dorn bottle and a 0.5-m ring net fitted with 363-μm mesh nylon monofilament cloth. Vertical net casts were made at a haul rate of 1 m/sec from 1 m off the bottom to the surface. Phytoplankton and zooplankton samples were preserved immediately upon collection with acid Lugol's solution and Formalin, respectively.

ANALYSIS

Water

Dissolved Oxygen--Azide modification of iodometric method (Standard Methods, 1971).

Biochemical Oxygen Demand--Five-day incubation (ibid.).

Ammonia--Phenolhypochlorite method (Zadorojny et al., 1973). Samples not filtered.

Nitrate+Nitrite--Cadmium reduction method (Standard Methods, 1971). Samples not filtered.

Orthophosphate--Ascorbic acid method (ibid.). Samples not filtered (see Table A-1 for corrections of turbidities).

Total Hydrolyzable Phosphate--Acid hydrolysis followed by ascorbic acid color development (ibid.). Samples not filtered.

Heavy Metals--Acidification with 0.4% HNO_3, followed by atomic absorption spectrometry (ibid.). Samples not filtered.
Perkin-Elmer Model 303 AAS used prior to 9/12/74;
Instrument Laboratory Model 453 AAS used on and after 9/12/74.

Table A-1. List of Significant[1] Turbidity Corrections to Apparent Orthophosphate Concentrations Measured on Unfiltered Samples

Stn	Depth (m)	Date	Turb. (JTU)	Ortho PO_4 (mg PO_4-P/l) Raw Data	Turb. Cttn.	Corr. Data
518	0.0	1-03-74	3.7	.040	-.011	.029
	11.2	1-17-74	2.9	.060	-.009	.051
	11.0	1-31-74	2.0	.030	-.006	.024
	0.0	3-01-74	2.7	.020	-.008	.012
	10.5		2.8	.020	-.088	.012
	11.2	4-25-74	2.4	.021	-.007	.014
	12.0	12-26-74	2.3	.011	-.007	.004
522	16.0	1-03-74	9.8	.060		ND[2]
	5.0	1-17-74	2.8	.040	-.008	.032
	0.0	3-01-74	2.7	.020	-.008	.012
	5.0		2.8	.020	-.008	.012
	10.0		2.6	.020	-.008	.012
	14.8		2.9	.020	-.009	.011
	5.0	3-15-74	2.4	.027	-.007	.020
	14.3	3-28-74	2.0	.020	-.006	.014
	14.3	6-06-74	2.2	.027	-.007	.020
	14.0	7-05-74	2.7	.095	-.008	.087
	14.0	7-18-74	2.2	.102	-.007	.095
	14.5	9-19-74	2.8	.271	-.008	.263
	0.0	12-26-74	3.4	.011	-.010	.001
	10.0		2.3	.012	-.007	.005
	16.0		2.5	.014	-.008	.006
526	14.0	1-03-74	2.7	.060	-.008	.052
	12.8	1-17-74	6.5	.060		ND[2]
	0.0	3-01-74	2.7	.020	-.008	.012
	14.8		3.4	.020	-.010	.010
	14.8	3-15-74	4.8	.032	-.014	.018
	13.8	4-25-74	2.0	.029	-.006	.023
	13.8	5-09-74	2.0	.010	-.006	.007
	0.0	6-06-74	2.1	.040	-.006	.034
	0.0	12-12-74	2.0	.012	-.006	.006

Table A-1. (continued)

Stn	Depth (m)	Date	Turb. (JTU)	Ortho PO_4 (mg PO_4-P/l) Raw Data	Turb. Cttn.	Corr. Data
526	0.0	12-26-74	2.6	.012	-.008	.004
	14.0		2.2	.013	-.007	.006
532	0.0	1-03-74	2.6	.040	-.008	.032
	10.0		3.0	.060	-.009	.051
	15.0		4.8	.060	-.014	.046
	0.0	3-01-74	2.7	.020	-.008	.012
	5.0		2.6	.020	-.008	.012
	10.0		2.4	.020	-.007	.013
	14.8		2.5	.020	-.008	.012
	5.0	4-25-74	2.0	.017	-.006	.011
	0.0	6-06-74	2.1	.023	-.006	.017
	5.0		2.0	.030	-.006	.024
	10.0		2.3	.024	-.007	.017
	14.9		2.2	.027	-.007	.020
	14.8	7-05-74	2.3	.125	-.007	.118
	14.5	7-18-74	2.1	.079	-.006	.073
	14.9	9-05-74	2.0	.186	-.006	.180
	14.9	10-17-74	6.3	.128		ND(2)

(1) Corrections are based on the factor, -.003 mg PO_4-P/l/JTU, for turbidities $\leq$ 5.0 JTU. Corrections of < .006 mg PO_4-P/l are not included.

(2) Not determined. The turbidity-apparent PO_4 relationship for turbidities > 5.0 JTU is unknown.

Temperature--Mercury thermometer. Shipboard analysis.

Salinity--Beckman Model RS-7B Salinometer (Standard Methods, 1971).

Conductivity--Hach Model 2510 Conductivity Meter (ibid.).

pH--Direct scale reading of a Beckman Model 76 Expanded-Scale pH Meter (ibid.). Laboratory Analysis.

Alkalinity--Potentiometric determination with a Beckman Model 76 Expanded-Scale pH meter (ibid.).

Suspended Solids--Total suspended matter method (ibid.).

Turbidity--Hach Model 2100A Turbidimeter (ibid.).

Total Coliforms--Membrane filter method with Mendo broth (ibid.).

Fecal Coliforms--Membrane filter method with MFC broth (ibid.).

Chlorophyll a--Trichromatic method, acetone extraction (ibid.).

Hardness--Computation from Ca and Mg (ibid.), which are determined by AAS (ibid.).

Solar Radiation--data provided by U.S. National Weather Service at Seattle-Tacoma International Airport.

Sediments

Chemical Oxygen Demand--Dichromate reflux method, (Standard Methods, 1971).

Total Volatile Solids--gravimetric determination, following drying 30 min. at 550 °C (ibid.).

Oils and Greases--Hexane/Soxhlet extraction method (ibid.).

Polarization (separation of animal or vegetable--and petroleum-based oils and greases)--Activated alumina method (ibid.).

Total Organic Nitrogen--Overnight leach of 5 g dried sediment in 50 ml of deionized distilled water (EPA, 1969) followed by Kjeldahl method (Standard Methods, 1971).

Total Phosphate--Persulfate method (Standard Methods, 1971).

Soluble Total Phosphate--Overnight leaching as for soluble organic nitrogen, followed by persulfate method, (ibid.).

Heavy Metals--Digestion with hot, conc. HNO_3, followed by analysis by Instrument Laboratory Model 453 AAS (ibid.).

Sedimentation Rates and Sediment Dating--The sediment dating was done by the ^{210}Pb technique of Goldberg (1964). The cores were cut into 2 cm sections. The outer 3 mm of each section was discarded; and the remainder was dried, pulverized, and stored in bottles. Fractions of selected sections were taken for determination of sedimentation rates. These samples were wet-ashed with $HClO_4$-HNO_3 (Smith, 1953), filtered, and brought to volume with 0.5 N HCl for ^{210}Po plating (the method used for measuring ^{210}Pb sedimentation rates). An aliquot was also taken for stable Pb analysis by AAS. The acid-insoluble material (labelled "insoluble fraction") was collected on a filter, dried, and weighed. The filtrate was stirred for 10 h at 50°C, together with a ^{208}Po tracer and a suspended 2.2-cm Ag disc coated on one side with Krylon (Beasley et al., 1973). Thus plated with the polonium isotopes, the Ag discs were then rinsed in distilled water, air-dried and radio-analyzed by Si surface-barrier detectors with pulse-height analyzers. The disintegration rate of ^{210}Po was measured by alpha spectroscopy and compared with the ^{208}Po added for tracing the chemical yield. Sedimentation rates were estimated by assumption of a time interval of 22.26 years for a 50 percent decrease in ^{210}Pb radioactivity between a given core section and another one below it.

Biota

Phytoplankton Counts, Identification and Volume Estimates--Only surface samples were used for counts and identification. The samples were initially allowed to settle for at least an hour in 1.3-ml counting chambers. They were then examined with a Leitz inverted microscope at 450 x for species identification and at 100 x for counting. All genera with four or more organisms/ml were recorded for each sample. Counts and identification to species level were made of volumetrically dominant and subdominant species. Counts were also made of all species that had an organism volume greater than 10^4 μ^3. The average length and width of counted colonial and filamentous organisms were measured with a Whipple grid. It was noted that the size of specific organisms often changed from sample to sample. Estimates of total phytoplankton volume densities were made by the use of these linear dimensions in conjunction with previously estimated cell volumes. Cell volumes were checked against the values reported by Pieterse (1974) and Munch (1972). Taxonomic keys used included those of Prescott (1962, 1970), Weber (1971), Smith (1950) and Bourelly (1966, 1968, 1970).

Zooplankton Identification--The key developed by Ward and Whipple was used (1959).

Macrofaunal Identification--Grab samples were examined visually. No keys required.